THE "INGENIA" INITIATIVE: A MULTIDISCIPLINARY SET OF SUBJECTS FOR PROMOTING THE CDIO METHODOLOGY IN A MASTER'S DEGREE IN INDUSTRIAL ENGINEERING

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ABSTRACT

The implementation of the "Bologna process" has culminated at ETSII – TU Madrid with the beginning of the Master's Degree in Industrial Engineering, in academic year 2014-15. The program has been successfully approved by the Spanish Agency for Accreditation (ANECA) and includes a set of parallel subjects, based on the CDIO methodology, denominated generally "INGENIA", linked to the Spanish "*ingeniar*" (to provide ingenious solutions), also related etymologically in Spanish with "*ingeniero*", engineer. INGENIA students live through the complete development process of complex products or systems liked to the different engineering majors at ETSII – TU Madrid. All subjects within the INGENIA initiative have an analogous structure and aim at the promotion similar professional outcomes, linked to the ability to design, implement and operate engineering systems, also focusing on teamwork and communication skills, and trying to systematically promote student creativity and their interest in social and ethical aspects of engineering for a sustainable World.

In this study we present the complete development of the INGENIA initiative, which includes subjects on: "Automotive Engineering", "Systems Engineering", "Electronic Systems", "Product Concept Development", "Biomedical Engineering Design", "Engineering Design", "Construction Engineering and Installations" and "Electrical Systems". During present academic year, groups of students in the different subjects of the INGENIA initiative, have lived through the complete development process of: a Formula-Student competition car, a cooperative group of drones, electronic systems for monitoring and improving the conditions of our university, innovative household products, biomedical devices, mechanical systems and machines, a modern beer brewery and a sustainable electricity supply network. Intensive use of supporting software, prototyping technologies and testing facilities at different labs from our university, has been a key aspect for adequately fulfilling all the CDIO steps, from the conception and design, to the implementation and operation.

Main benefits, lessons learned and challenges, linked to this multidisciplinary and multi-subject INGENIA CDIO initiative, are analyzed, taking into account the results from 2014-2015 academic course. Students' and teachers' expectations and opinions have been systematically gathered and are also detailed and discussed. To our knowledge, the INGENIA initiative constitutes the first integral application of the CDIO methodology to the field of Industrial Engineering in our country.

KEYWORDS

CDIO as Context, Integrated Curriculum, Integrated Learning Experiences, Active Learning. (Standards: 1, 3, 7, 8).

INTRODUCTION

Student motivation and active engagement to their own learning process is a key success factor in Higher Education, especially in Science and Engineering paths, as recognized and highlighted in several studies, reports and declarations, such as the Bologna Declaration and the subsequent related declarations from Prague, Berlin, Bergen, London, Leuven and Budapest-Vienna, aimed at the implementation of the European Higher Education Area (EHEA). Making students drivers of change is perhaps the most effective part of a global strategy, for the promotion of professional skills in Engineering Education (Shuman, et al. 2005, Díaz Lantada, et al. 2013). Problem- or project-based learning (typically PBL) methodologies clearly tend to motivate students to participate and become involved in their own learning process and is an excellent way of analysing whether students have acquired the basic concepts taught in the theory classes and if they are capable of applying them in real situations. These PBL experiences have proven to be effective in primary, secondary and university education and in scientific-technological, bio-sanitary, humanistic and artistic contexts. In consequence, most technical universities, before awarding the engineering degree, almost always include the standard final degree project as part of the studies, which, basically, is a PBL learning experience. In direct connection with the promotion of project-based learning methodologies worldwide, even though its holistic approach to engineering education development goes far beyond project-based learning, the CDIO™ Initiative (www.cdio.org) is probably the most ambitious approach. The CDIO™ Initiative is focused on the establishment of an innovative educational framework for producing the engineers of the future, by means of providing students with an education stressing engineering fundamentals by means of “Conceiving - Designing - Implementing – Operating” (CDIO) real-world systems, processes and products (Crawley, et al. 2007). Throughout the world, CDIO Initiative collaborators are adopting CDIO as the framework of their curricular planning and outcome-based assessment. CDIO also promotes collaboration and sharing of good practices among engineering educational institutions worldwide.

The main purpose of present study is to detail current actuations at ETSII – TU Madrid oriented to a more systematic integration of CDIO experiences within our program 6-year integral program of Industrial Engineering (Grade + Master’s Degree), paying special attention to the “INGENIA” initiative, which has been implemented for the first time in current academic year, within our new Master’s Degree in Industrial Engineering. In addition, we would like that present article may serve as introduction, support and discussion document for our forthcoming application for becoming members of the International CDIO Initiative.

THE “INGENIA” INITIATIVE: INTEGRATED PROMOTION OF CDIO INITIATIVES

The ETSII – TU Madrid (www.etsii.upm.es, see Figure 1) has been promoting student-centred teaching-learning activities, according to the aims of the Bologna Declaration, well before the official establishment of the European Area of Higher Education (Vera, et al. 2006). In the last years we would like to highlight the Innova.Edu projects, funded by our centre during the academic years 2004-2005 and 2005-2006, which helped to promote several project-based learning activities in different subjects and to set common practices among our teaching staff for activities in the field of “conceive, design, implement & operate”. Additional educational innovation projects, funded by our University since 2007, have helped us to establish supplementary best practices for promoting student motivation, to implement novel subjects linked to project-based learning, to enhance our faculty teaching skills, to improve our assessment and evaluation plans, among other innovations. Such improvements have led to the Accreditation of our Industrial Engineering program by ABET (www.abet.org) in 2010.

Figure 1. ETSII – TU Madrid Campus, main hall and collaborative learning environments.

The level of commitment of our teachers with these educational innovation activities is noteworthy, as the teaching innovation experiences carried out in the last ten years have led to the foundation of 17 Teaching Innovation Groups at ETSII – TU Madrid, hence leading the ranking of teaching innovation among all UPM centres. The historical background was previously reviewed and presented at the 10th International CDIO Conference, held in Barcelona in 2014 (Díaz Lantada, et al. 2014). In any case, it is important to highlight that, at ETSII – TU Madrid, we are deeply concerned about students' involvement in their own learning process and implicated in strategic actuations for the promotion of project-based learning activities, linked to real products and systems, as drivers of curricular planning, of continuously evolving teaching-learning methodologies and processes, and of an outcome-based assessment. **We are working towards providing an integrated support framework for driving the aforementioned PBL actuations, searching for common actuation principles, based on the "conceive-design-implement-operate" guidelines, as we consider it truly beneficial for students and teachers.** The implementation of the **"INGENIA" Initiative** is the key for achieving standardized and complete CDIO experiences (from the conceptual stage to the operational phase) and for providing the 100% of our students with the opportunity of living the whole development process of a product or system, as detailed further on.

The implementation of Bologna process has culminated at ETSII – TU Madrid with the beginning of the Master's Degree in Industrial Engineering, in current academic year 2014-15. The program was successfully approved in 2014 by the Spanish Agency for Accreditation (ANECA), with the inclusion of a set of subjects based upon the CDIO methodology denominated generally "INGENIA", an acronym from the Spanish verb "*ingeniar*" (to provide ingenious solutions), also related etymologically in Spanish with the word "*ingeniero*" (engineer). INGENIA students experience the complete development process of a complex product or system and there are different kinds of subjects (and projects), within the initiative, covering most of the engineering majors at ETSII – TU Madrid. Students choose among the different INGENIA subjects (and projects), depending on their personal interests.

The INGENIA subjects are compulsory for all students enrolled in the first year of the Master's Degree program at ETSII – TU Madrid (a two-year program with 120 ECTS after a four-year Grade in Industrial Technologies with 240 ECTS). The subjects (with a similar CDIO orientation but offering different topics and projects) are 12 ECTS equivalent, which correspond to a student workload between 300 to 360 hours, distributed along two semesters with the following structure: 120 hours of supervised work plus between 180 to 240 hours of personal student work, organised usually in teamworks. Professor supervised part of the subjects is divided into 30 hours dedicated to adapt basic theoretical knowledge derived from other subjects to those directly related with the project, and a second set of 60 hours is devoted to practical work in the lab, with professor supervised sessions. Students also receive two seminars of 15 hours; one oriented to transversal outcomes, in particular, workshops on teamwork, communication skills and creativity techniques, and the other one about social responsibility issues such as environmental impact, social, political, security, health, etc. The distribution of these lectures, practical sessions, seminars and workshops, is distributed along the 28 weeks of the two semesters of the first year, resulting in 5 hours per week of lectures or practical sessions in the regular schedule of students.

Placing the INGENIA subjects in the first year of a 120 ECTS program is indeed interesting, as additional 12 ECTS are devoted to the final degree thesis normally during the second year. Therefore, at least 20% of the whole Master's Degree is devoted to project-based learning aimed at the complete development of engineering products and systems. Program structure is detailed in Figure 2 and the integration of CDIO activities can be easily appreciated (INGENIA subjects in pale blue and Final Master's Thesis in pale green). In addition, the INGENIA subjects are helping us to complement our competence-based strategy, in accordance with CDIO Standards 1, 3, 7 & 8, by placing special emphasis on several professional skills difficult to obtain in more traditional teacher-centred activities, such as conventional master classes and expert talks. Expected outcomes include the promotion of: students' ability to apply knowledge of mathematics, science and engineering, students' ability to design experiments and interpret data, students' ability to design engineering systems and components to meet desired goals, students' ability to communicate effectively and to work in multidisciplinary teams, or students' ability to use modern resources, in accordance with the ABET professional skills our program pursues (Shuman, et al. 2005). Table 2 includes the different CDIO topics (or subjects) taught within the INGENIA scheme for the academic year 2014-2015, covering several disciplines.

Hours/week	THIRD SEMESTER	ECTS	Hours/week	FOURTH SEMESTER	ECTS
	Final Master's Thesis	6		Final Master's Thesis	6
6	Curricular configuration	9	6	Curricular configuration	9
2	3 specialization subjects (Automation & Electronical, Chemical, Electrical, Energetic, Materials, Mechanical, Construction, Org.)	3	2	3 specialization subjects (Automation & Electronical, Chemical, Electrical, Energetic, Materials, Mechanical, Construction, Org.)	3
2		3	2		3
2		3	2		3
2	1 subject on Industrial Installations	3	2	1 subject on Industrial Management	3
2	1 subject on Industrial Technologies	3	2	1 subject on Industrial Technologies	3

Hours/week	FIRST SEMESTER	ECTS	Hours/week	SECOND SEMESTER	ECTS
4	INGENIA (first part)	6	4	INGENIA (second part)	6
2	2 subjects on Industrial Management	3	2	2 subjects on Industrial Management	3
2		3	2		3
2	2 subjects on Industrial Installations	3	2	2 subjects on Industrial Installations	3
2		3	2		3
2	4 subjects on Industrial Technologies	3	2	4 subjects on Industrial Technologies	3
2		3	2		3
2		3	2		3
2		3	2		3

Figure 2. Program structure (Master's Degree in Industrial Engineering).
120 ECTS program with at least 20% devotion to project-based learning activities.

Table 1. CDIO topics of the INGENIA subjects for the academic year 2014-2015.

Different INGENIA Subjects	Product / system developed & objective
Formula Student	Students take part in the complete development project of a competition car, from the conceptual design, to the final competition.
Engineering design: Machine development projects	Students live the whole process of creating an innovative machine, from the conceptual design stage, to the final trials with real prototypes, searching for design improvements.
Development of daylife products / household goods	Students live the whole process of designing innovative products, from the concept step, to final simulations and trials with prototypes.
Smart systems engineering	Students experience the process of designing a smart system, using state-of-the-art engineering resources and taking account of the whole life-cycle. (A set of co-operative drones in current year).
Development of electronic devices	Students live the whole process of creating a new electronic product, oriented to improving daylife in our ETSII-UPM, from the concept, to the prototyping stage and trials.
Development and management of industrial construction projects	Students experiment with information management and project planning resources applied to a real industrial construction project (A beer-factory in current academic year).
Development of electricity supply networks	Students live the development project of an electricity supply network, from an initial renewable energy source to population.
Biomedical engineering design	Students experience the process of creating an innovative medical device, from the conceptual stage, to the final trials with prototypes.

Some of the proposals for the INGENIA subjects evolve from previous experiences, but most of them are novel initiatives consequence of the progressive involvement of our teaching staff in student-based teaching-learning methodologies for the promotion of integrated learning experiences (7th CDIO Standard) and of active learning (8th CDIO Standard). The topics from Table 2 cover most specializations of our Master's Degree in Industrial Engineering and we believe that all of them are interesting, although improving the offer is a key-point, as will be discussed further on. As additional reflection, the proposed two-semester structure for the INGENIA subjects is very appropriate, as the "conceive" and "design" phases are adequately carried out during the first semester and the "implement" and "operate" stages are tackled in the second semester. A whole academic year is ideal for maturing the development process of complex products and systems and is helping us to improve several prior experiences, limited to design and simulation activities, with the benefits from obtaining final prototypes and carrying out operational trials.

Regarding assessment, we are facing and managing the typical problems that arise when assessing teamwork activities. First of all, the proposed projects are complex enough to promote positive interdependence between members of the team, so that each of the members is needed for the overall success and that there is enough workload to let all students work hard and enjoy the experience, thanks to learning a lot. In addition, we are encouraging individual assessment, complementing the teamwork activities with individual deliveries and during the public presentations of their final results. The evaluation of professional skills counts with the help of ad hoc designed rubrics, as part of an integral framework for the promotion of engineering education beyond technical skills, consequence of recent educational innovation projects (Hernández Bayo, et al., 2014). Main results, lessons learned and key challenges of the first implementation of the INGENIA subjects are detailed in the following section.

FIRST IMPLEMENTATION OF THE "INGENIA" INITIATIVE: MAIN RESULTS, LESSONS LEARNED AND CHALLENGES

During academic course 2014-2015 all the students from the first promotion of our Master's Degree in Industrial Engineering (160 engineering graduates) have taken part in the different subjects of the INGENIA Initiative, distributed as detailed in Table 2. A total of 68 teachers have been involved in the different subjects, which have been supervised by the team of our Vice-Dean of Studies and supported by experts in communication, teamwork, creativity, conflict management and psychology, with some seminars for training our teaching staff and a common Moodle site for sharing resources and good practices among the different subjects. When considering our possible incorporation to the International CDIO Initiative, we understand that a central success factor is teacher implication and teaching competence. Therefore during the first semester, several seminars on the aforementioned professional skills, open to students and teachers, have been carried out by internal and external experts. It is also important to highlight that, only in relation to the INGENIA Initiative, more than the 20% of our active teaching staff is directly linked to the promotion of CDIO-related tasks. In addition, the 100% of our teachers collaborate in other PBL activities, such as the planning and supervision of Master Theses. In the different subjects, the conceptual stage is supported by creativity-promotion tools such as TRIZ, morphological boxes and systematic procedures for promoting the generation, combination and selection of ideas. The design stage counts with industrial state-of-the-art modeling and simulation software of main engineering disciplines. Several labs help with the implementation and operation stages with resources including: 3D printers, rapid prototyping facilities, Arduino kits, libraries of sensors and actuators and conventional manufacturing and testing resources. Some results from students' designs, simulations, prototypes and trials are included in Figure 3, although the final results will be obtained along the second semester just before the 11^{th} International CDIO Conference, where we hope to discuss them with colleagues from partner universities.

Table 2. Main figures of the INGENIA subjects for the academic year 2014-2015.

Different INGENIA Subjects	Students / Subject	Groups / Subject	Teachers / Subject	Student – Teacher ratio
Formula Student	14	1 project, 5 divisions	6	2.3
Engineering design: Machine development project	23	5	6	3.8
Development of daylife products / household goods	14	4	10	1.4
Smart systems engineering	11	1 project, 5 orientations	7	1.6
Development of electronic devices	17	4	12	1.4
Development and management of industrial construction projects	27	1	6	4.5
Development of an electricity supply network	23	1 project, 3 subsystems	15	1.5
Biomedical engineering design	28	6	6	4.7

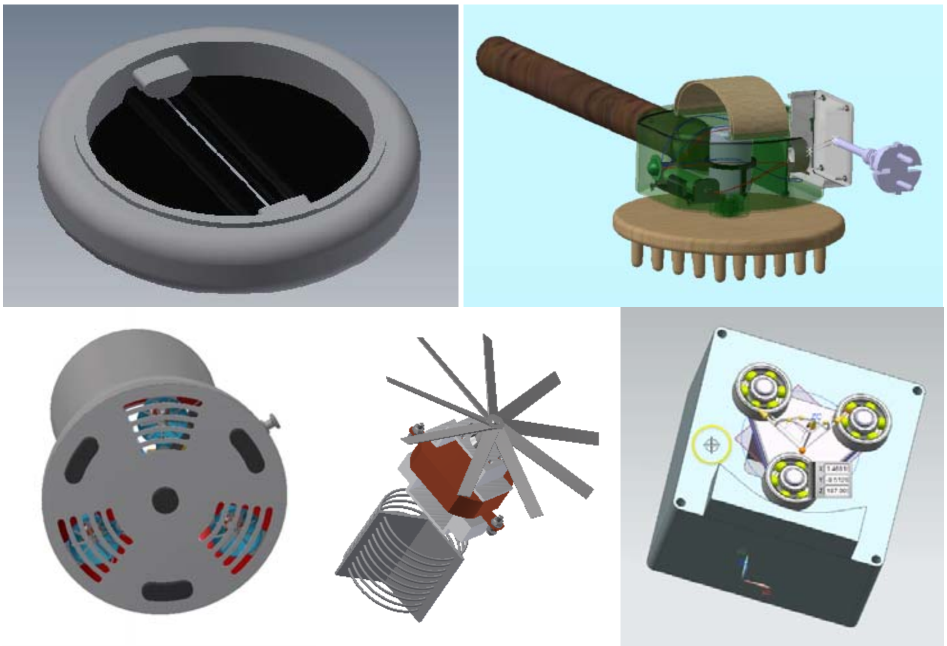

Figure 3. Some case studies and preliminary results from students' designs. a) Instrumented heart valve. b) Automatic sponge. c) Umbrella dryer. d) CAD of a peristaltic pump.

Among already detected positive results, it is very important to highlight the following aspects, which we believe are intrinsically connected with a well implemented CDIO framework within the Master's Degree in Industrial Engineering and with successful PBL subjects:
- Students' success ratio and attendance to formal lessons is importantly improved.
- The interaction between teachers and students has experienced a relevant increase.
- Intra- and inter-departmental communication has been promoted.

As preliminary summary of results, Table 3 includes some figures related to student and teacher success, motivation and implication in their subjects before and after the INGENIA Initiative. The positive effect of shifting towards CDIO related methodologies can be clearly appreciated. It is necessary to indicate that the benefits affect not only learning and acquisition of outcomes, but also student and teacher motivation and mutual relation in a very special way, which is starting to influence the overall ambience of learning, collaboration and respect present in our novel Master's Degree in Industrial Engineering. Such positive aspects clearly rely on an important increase of teacher dedication outside the classroom to the CDIO-based subject, but the general impression among the different teachers and subjects is that such additional dedication is compensated by the highly satisfactory results. In addition, the practical activities of the new subjects are more expensive to implement, than more traditional practicals, as can be appreciated from the data in Table 3. However, the additional amount lays between 10.000€ and 20.000€ for a whole set of new subject allowing all students of our Master's Degree live through the complete development process of a complex engineering system. Again, the general impression is that the results are worth the effort. In addition, the INGENIA Initiative and the topics covered have proved to be of real interest for several enterprises, with which we normally collaborate by means of Enterprise-University Chairs. Our intention is to incorporate them into the initiative as key players for proposing complex projects, for implementing student competitions and even for evaluating our students. The proposed initiative may well be a way of calling the attention of additional enterprises for new patronages.

Table 3. Some figures related to student and teacher motivation and implication in their subjects before and after the INGENIA Initiative. *According to data of the first semester.

Control aspect	In conventional subjects before the promotion of student-centred approaches	In subjects of the INGENIA Initiative with a student-centred approach
Success ratio	45% – 75%	>95%*
Student attendance to scheduled lessons	35% – 65%	>85%
Typical number of answers to debate questions	1 – 3	6 – 8
Typical number of student questions / hour	2 – 5	4 – 7
Number of teachers inside the classroom at once	1 – 2	2 – 6
Frequency of meetings between the teachers of the same subject	2 / semester	3 / month
Frequency of meetings between the teachers of different departments	1 / semester	1 / month
Num. of interactions with students outside the classroom / week	0 – 3	5 – 10
Resources needed for practical activities	0 – 100 € / student for practical sessions	50 – 100 € / student for practical sessions 500 – 1.000 € / group for prototyping tasks
Number of professional skills promoted and assessed	1 – 4	8 – 10
Hours devoted by the teachers outside the classroom / class hour	0.5 – 1	2 – 4

Regarding main challenges, a novel system for an improved management of teaching-learning spaces is being developed, as the set of INGENIA subjects requires not only conventional classrooms, but also computer rooms, labs and collaborative environments, which must be handled in a flexible way. Another essential aspect, expecting 400-450 students in our Master's Degree in Industrial Engineering for academic course 2015-2016, is increasing the number of INGENIA subjects and the topics covered, in order to have enough offer and not to increase the number of students per subject above 30-40 students, which may limit their positive impacts. Some areas including nuclear engineering, chemical engineering, materials science and management still need to be covered. Improving the teaching and assessment skills of our teaching staff, regarding professional outcomes, is also a relevant challenge, which must be tackled in with a continuous improvement strategy.

DISCUSSION AND FUTURE PROPOSALS

We believe that the described INGENIA framework, for the systematic promotion of "conceive-design-implement-operate" teaching learning activities in our Master's Degree in Industrial Engineering, is completely aligned with the CDIO framework. Having a look at the CDIO adoption process diagram (www.cdio.org), it is important to note that our engineering context and previous experiences are very adequate for implementing such framework. The curriculum is already developed and the outcomes are clear and validated by ABET, although we understand that CDIO holistic approach to curriculum development goes beyond that and must be further improved and assessed.

The teaching-learning methods from our colleagues, the available facilities and the recently developed support resources for the evaluation of professional skills are in accordance with the overall strategy and have brought us to the point of launching the integrated initiative. In the last years, several collaborative sessions have allowed us to provide a final adjustment to our faculty CDIO and teaching skills. Although we have focused here on the flagship INGENIA project, we are conscious that our curriculum must be complemented with discipline-led activities and professional practices. In fact, 18 ECTS of the Master`s Degree in Industrial Engineering are devoted to other actions, also aligned with the CDIO approach, such as co-ops with industry and research labs, collaboration in social and educational projects or technical seminars and workshops, among others, so that students live CDIO-related experiences in both years of the Master's Degree in Industrial Engineering. Finally, our attendance to the 2015 Cheng-Du 11th International CDIO Conference will provide us the excellent opportunity of discussing the INGENIA approach with experts of CDIO framework. Their comments and proposals for improvement will help us to adjust our views and strategy, so as to obtain optimal results.

CONCLUSIONS

Present study has detailed current efforts aimed at a more systematic integration and promotion of CDIO activities within our Industrial Engineering program. The detailed set of "INGENIA" subjects is the key element of our strategy, towards such systematic integration and promotion of CDIO activities, as we have also discussed. INGENIA subjects are compulsory for all students enrolled in the first year of the Master's Program at ETSII – TU Madrid and are an ideal complement to (as well as preparation for) other more traditional project-based learning activities, such as the Master's Theses carried out by students at the end of the program. We truly hope that present summary may be useful as introduction, support and discussion document for our forthcoming application for becoming members of the international CDIO Initiative.

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